



Vertical Launch Third Harmonic ECRH of H-mode on TCV and Access to Quasi-Stationary ELM-free H-mode

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OVERVIEW

- Introduction & Motivation
- X3 system
- X3 heating of H-mode
- Quasi-Stationary ELM-free H-mode (QSEFHM) regime
- Summary & Conclusions

INTRODUCTION

- TCV is a medium sized tokamak

$$I_p \leq 1 \text{ MA}$$

$$B_{\text{tor}} < 1.54 \text{ T (1.45 T typical)}$$

$$a \approx 25 \text{ cm}$$

$$\kappa \leq 2.8 \text{ (extreme elongation)}$$

- 6 Gyrotrons at 82.7 GHz for ECRH/ECCD

current profile control

e-ITB

fully non-inductive operation

$$n_{e,\text{max}} < 4.2 \times 10^{19} \text{ m}^{-3}$$

- Electron Bernstein Wave Heating (EBW)

$$n_{e,\text{max}} > 20 \times 10^{19} \text{ m}^{-3}$$

Mück A. et al PRL **98** 175004 (2007)

- ***One of the main goals of TCV is to study plasma near the β -limit***

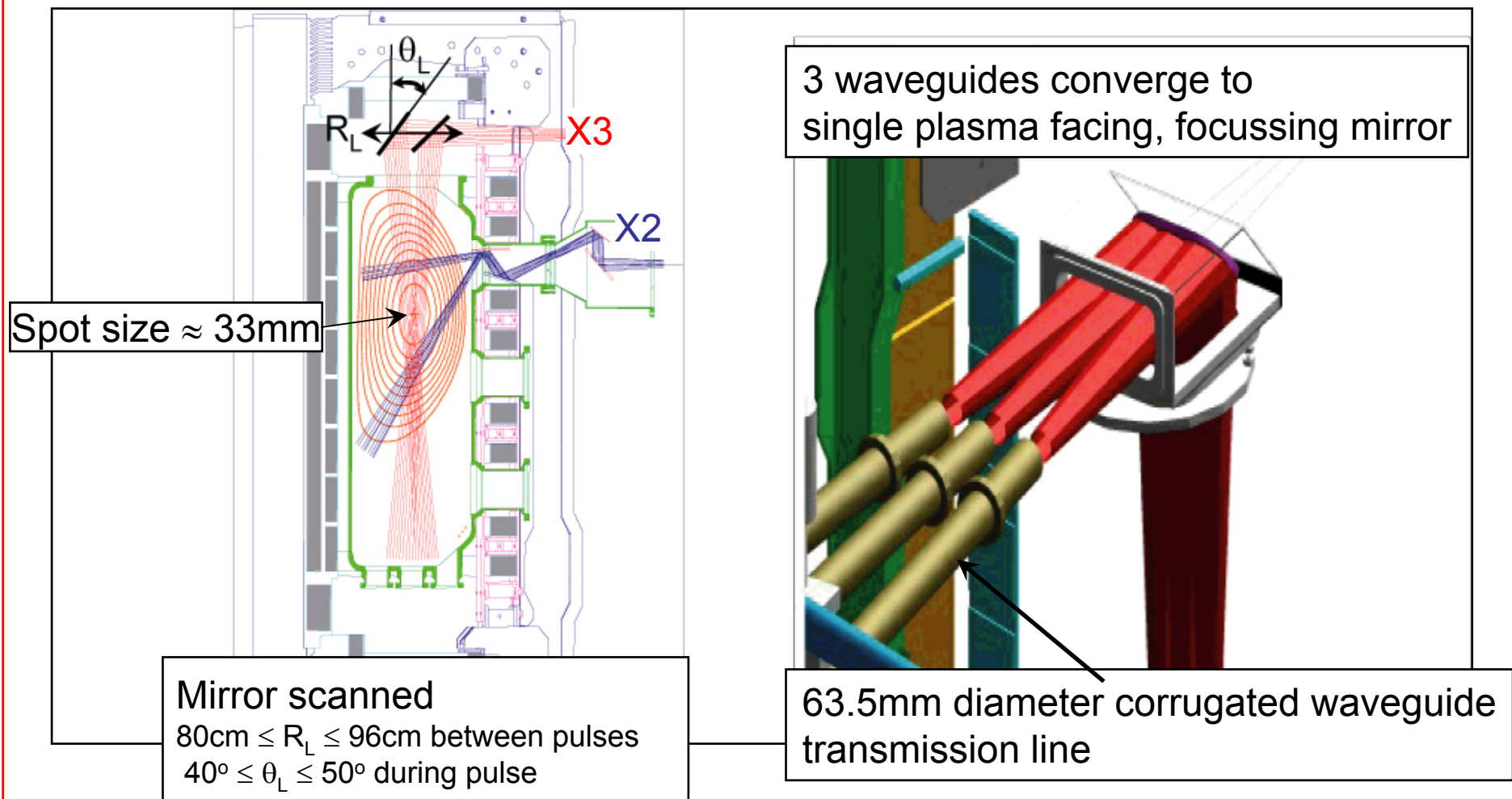
- Heat H-mode at high density



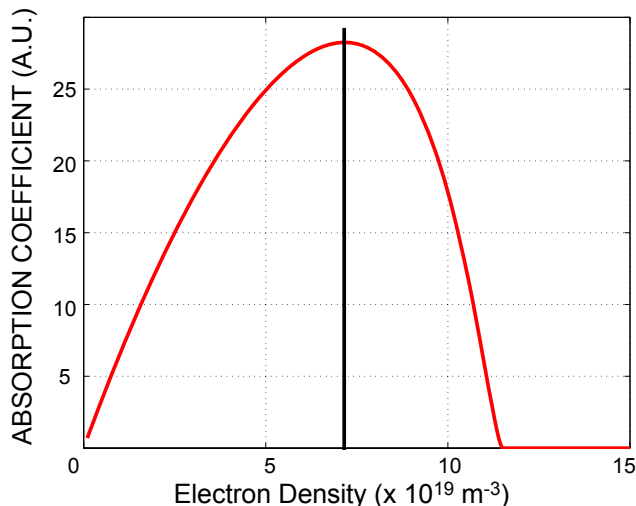
X3 SYSTEM

- 3, 118GHz, 480kW gyrotrons; top launch to maximise path along X3 resonance and increase absorption
- Pulse length 2.0sec, limited by the power supplies
- *Liquid N2 cooled sapphire output window*
window is limiting factor for output power
CVD diamond window installed in one gyrotron
→ **increase power**
- Gyrotron power can be modulated but power ramps difficult
- Launch X-mode
Matching Optics Unit (MOU) → arbitrary polarisation
- Transmission line is $\approx 95\%$ efficient so ≈ 1.37 MW available at the plasma

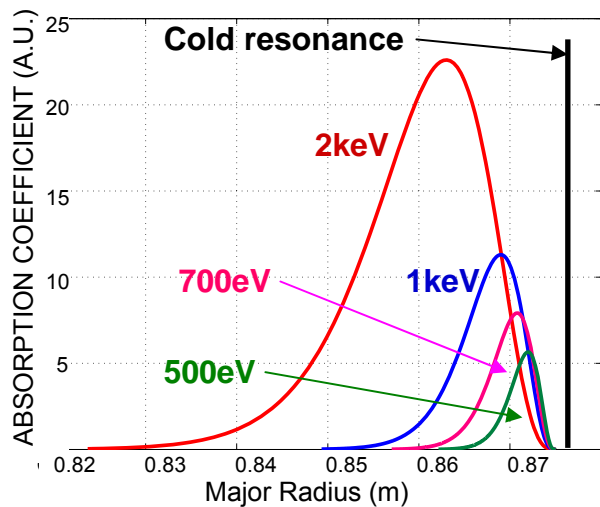
X3 SYSTEM : LAUNCHER



X3 HEATING OF HMODE



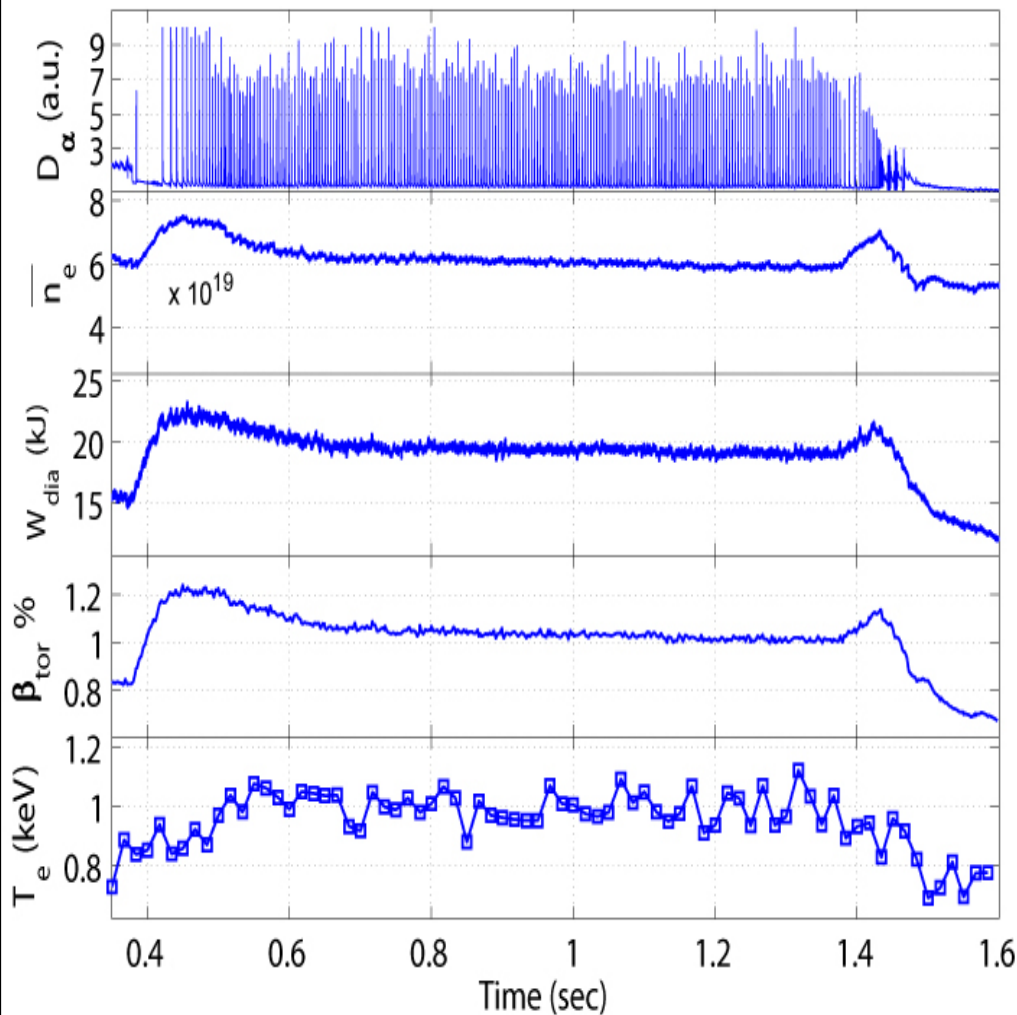
- $n_e \approx 7.1 \times 10^{19} \text{ m}^{-3}$ for best absorption
- Work typically at $n_e \approx 6 \times 10^{19} \text{ m}^{-3}$ so that refraction is avoided
- $\alpha_{X3, \text{vertical}} \propto T_e$ so if we couple X3 well enough the absorption increases quickly



- relativistic broadening
- At $T_e > 2\text{keV}$ not sensitive density perturbations (ELMs for example) & first pass absorption $> 75\%$

X3 HEATING OF H-MODE ; TARGET

Overview of #29469



Single null diverted plasma

Ion grad-B drift away from the X-point

$$390 \text{ kA} \leq I_p \leq 420 \text{ kA}$$

$$B_{\text{tor}} = 1.45 \text{ T}$$

$$n_{e,\text{max}} \approx 6 \times 10^{19} \text{ m}^{-3} \text{ (25\% } n_{e,\text{Greenwald}})$$

$$\delta_{95} \approx 0.36$$

$$\kappa_{95} \approx 1.65$$

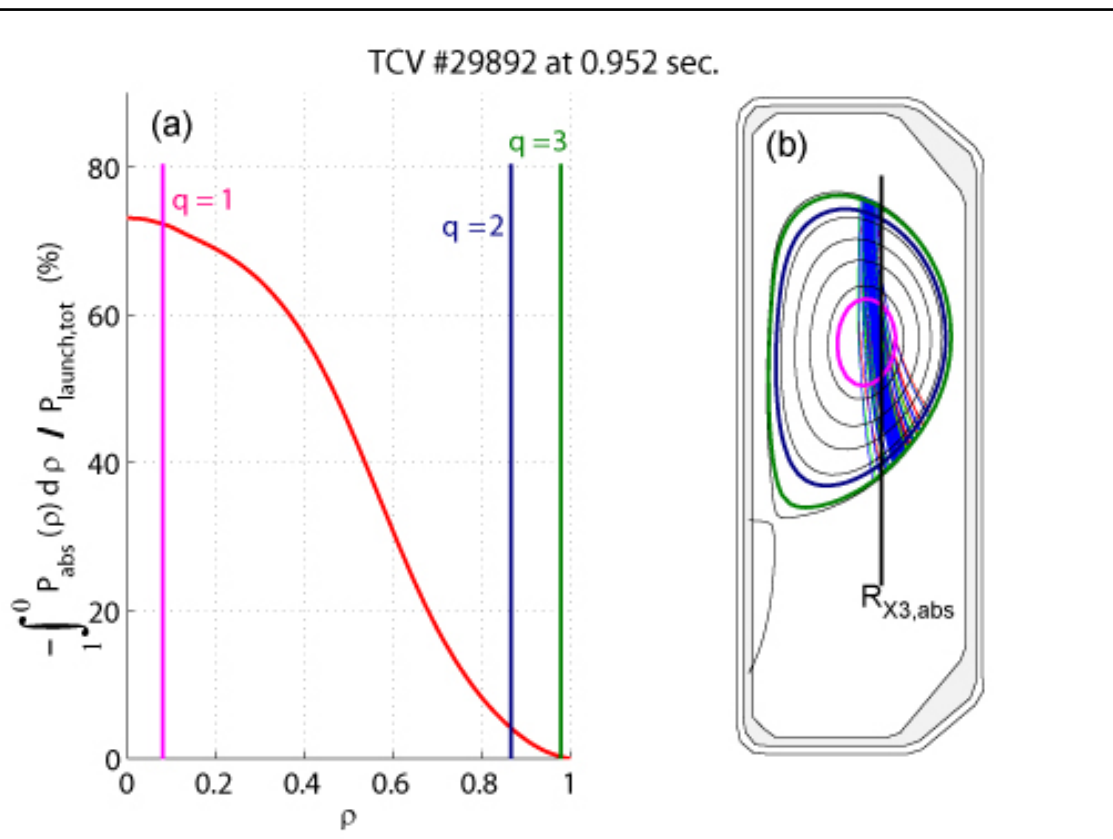
$$q_{95} \approx 2.4$$

$$d_{\text{inner}} \approx 3 \text{ cm}$$

$$\delta W_{\text{DIA,ELM}} / W_{\text{DIA}} \approx 4\%$$

IPB98(y,2) describes confinement

X3 HEATING OF H-MODE ON TCV

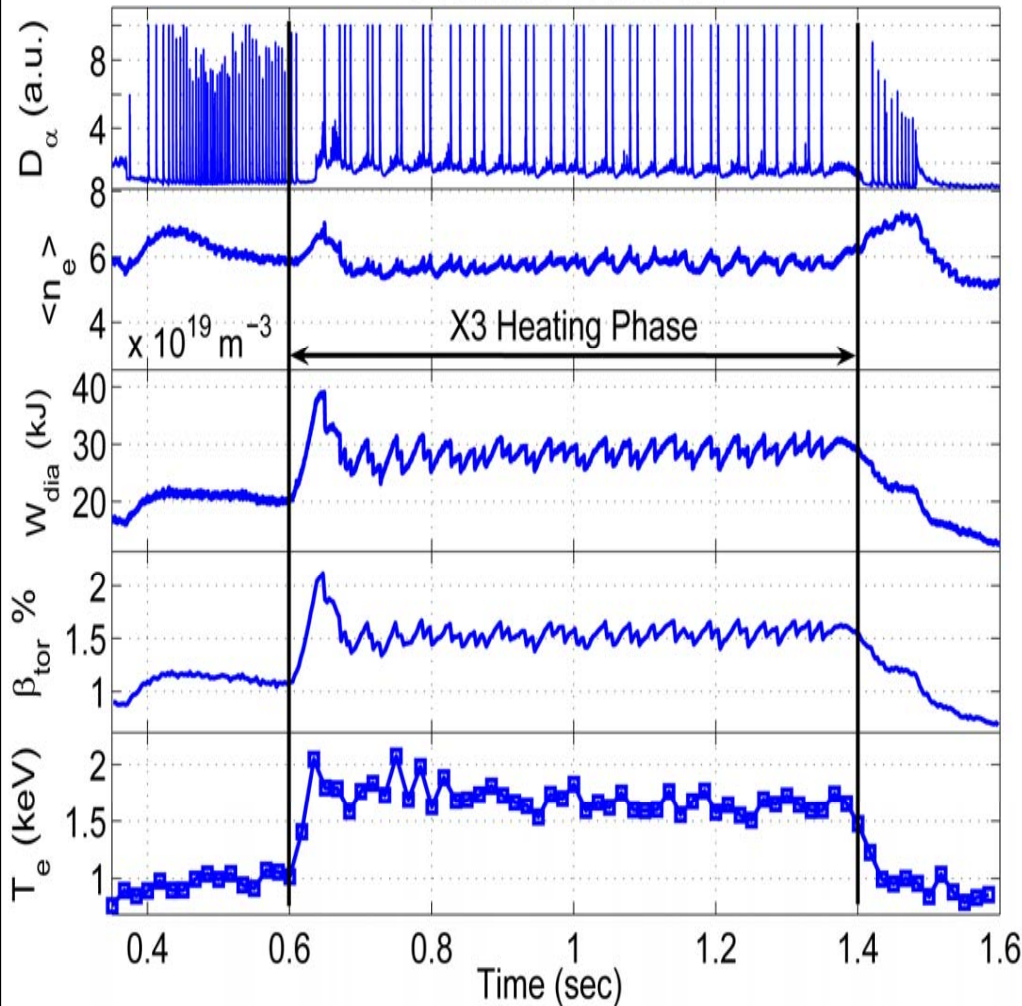


- Estimates of X3 absorption obtained using TORAY-GA
- Arnoux et al¹ have validated TORAY-GA use in H-mode → *good agreement between TORAY_GA & measures using modulated ECH & the response of a diamagnetic loop*
- These plasmas are thermal
- Absorption not localised & most heating takes place in a region $0.1 < \rho < 0.8$

¹ Arnoux, G, PhD thesis FL #3401 (2005) & Plasma Phys. Control. Fusion **47**, 295 (2005)

X3 HEATING OF H-MODE IS 'ROBUST'

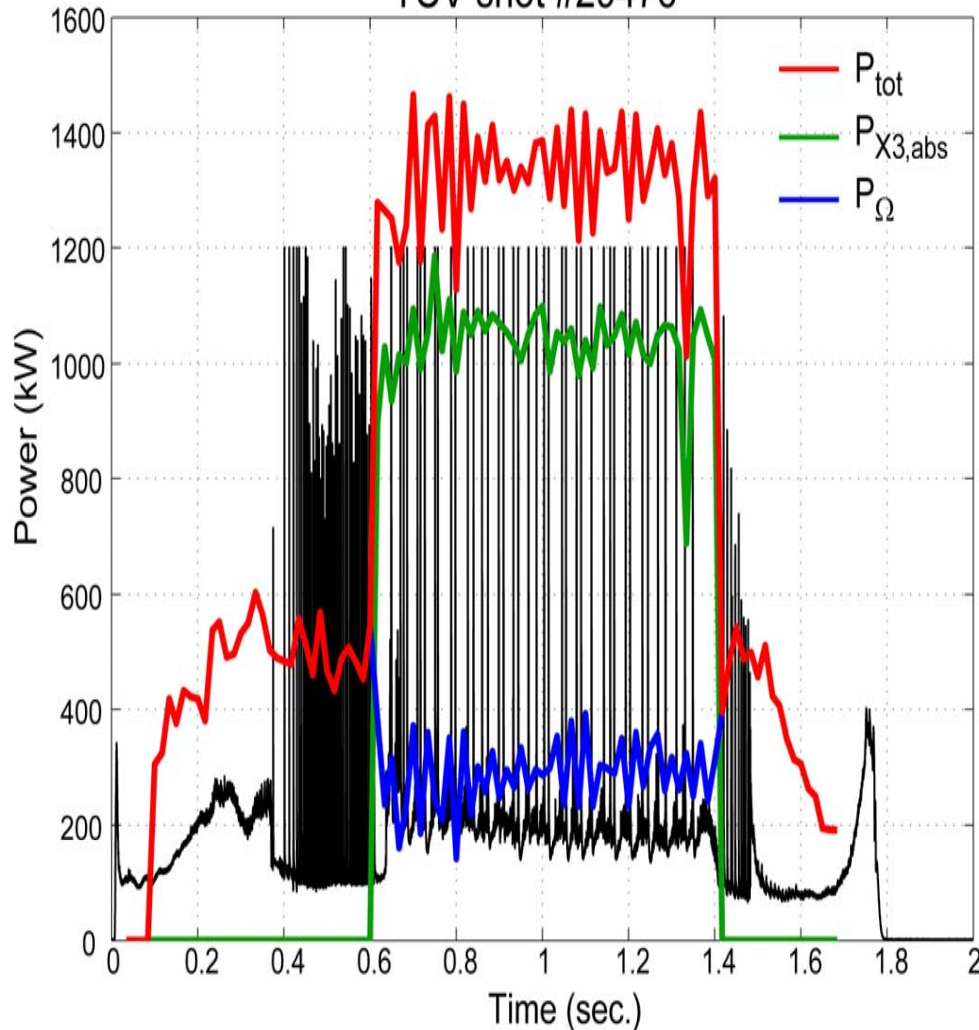
Overview of #29476



- ELMy H-mode successfully heated using vertical X3 ECRH
- $\delta \langle n_e \rangle / \langle n_e \rangle \approx 0.07$; ELMs do not degrade the X3 heating performance
- In this case X3 coupled fraction was $\approx 70\%$ (960 kW)

X3 HEATING OF H-MODE IS 'ROBUST'

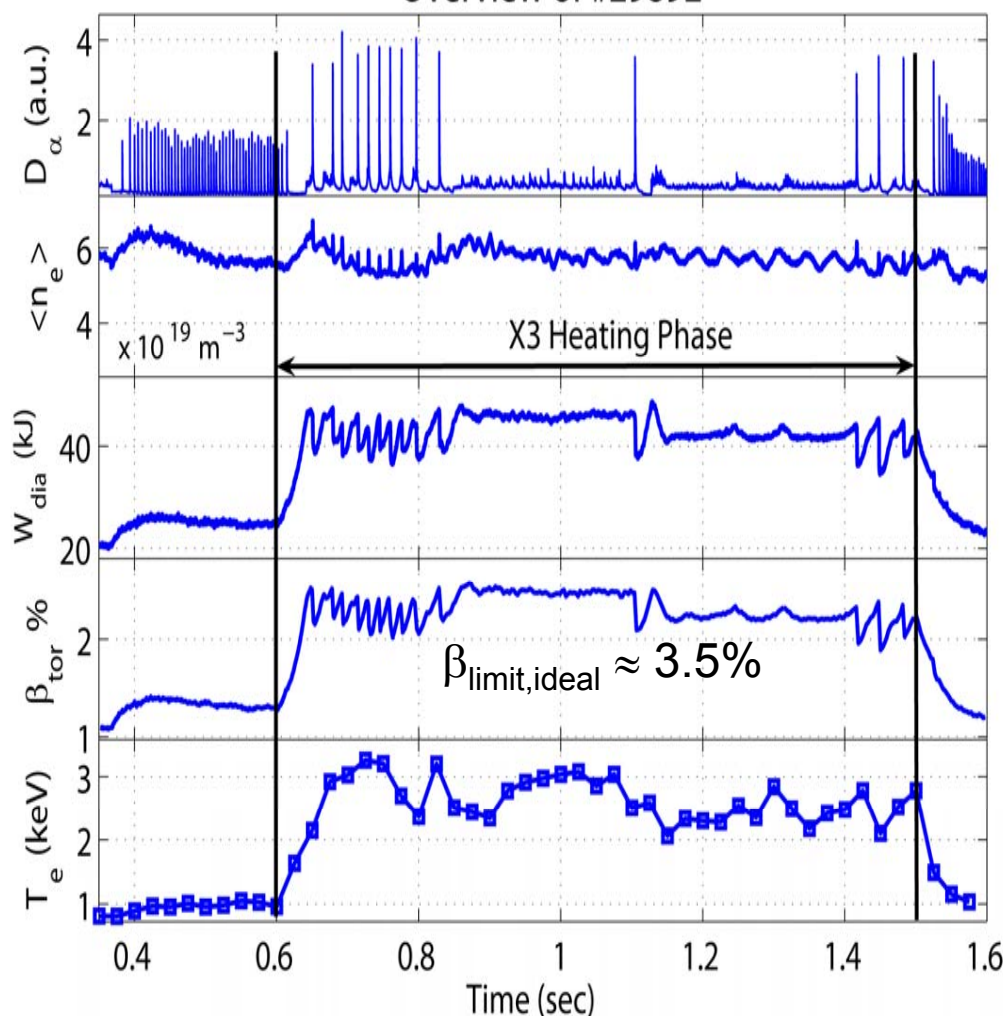
TCV shot #29476



- $P_{\Omega} \approx 500\text{kW}$ falls to $\approx 300\text{kW}$
- X3 absorption starts at 40% and quickly rises to its final 70%

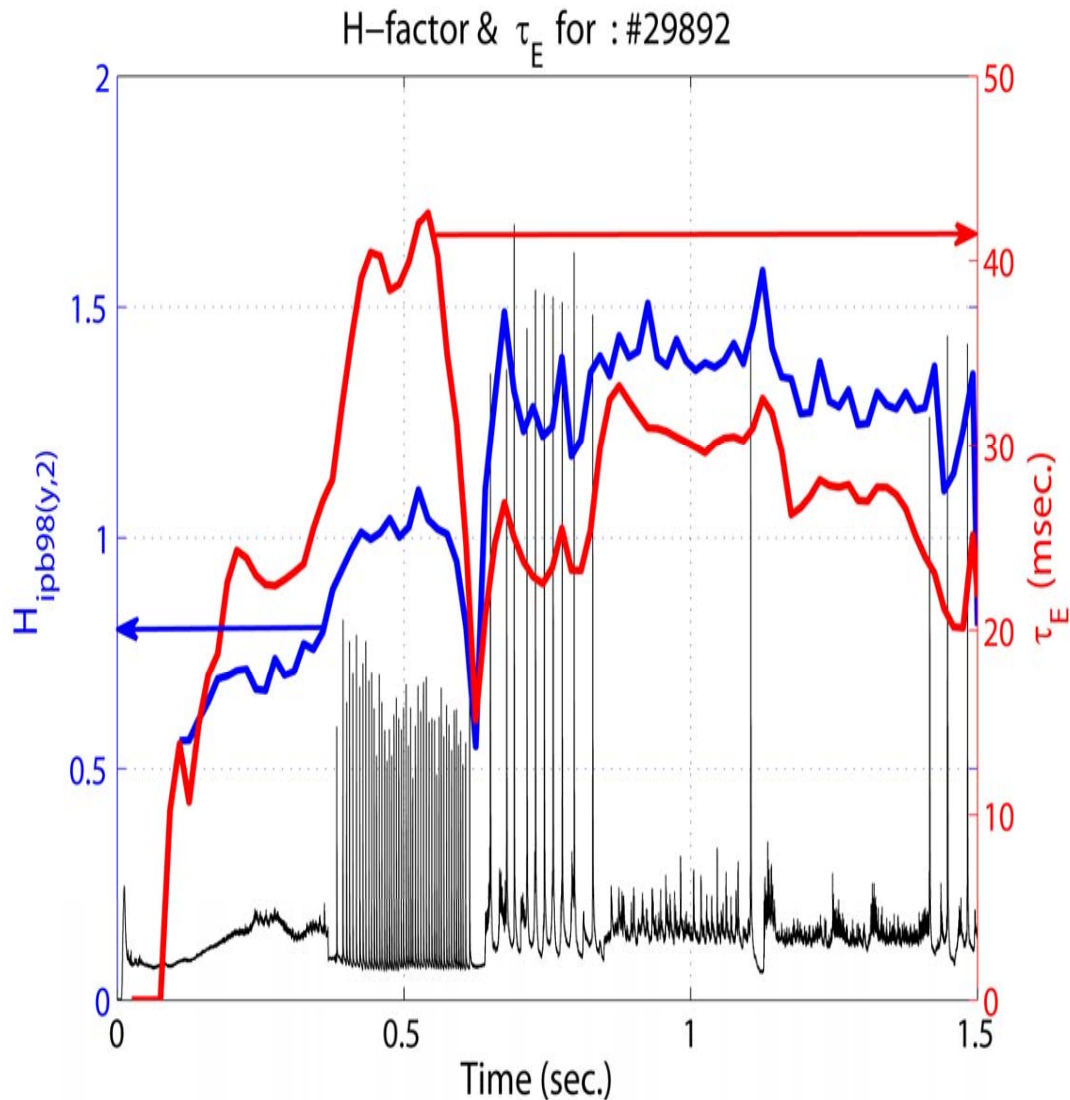
QSEFHM : GENERAL

Overview of #29892



- Operating regime new to TCV
- Requires > 1.2 MW coupled X3 power
- The transition to QSEFHM is not yet understood
- High confinement
- Stationary density
- $Z_{\text{eff}} \approx 2.5$; $P_{\text{rad}} \approx 300\text{kW}$
- no impurity accumulation
- Discharge exhibits sawteeth
- Energy content doubles

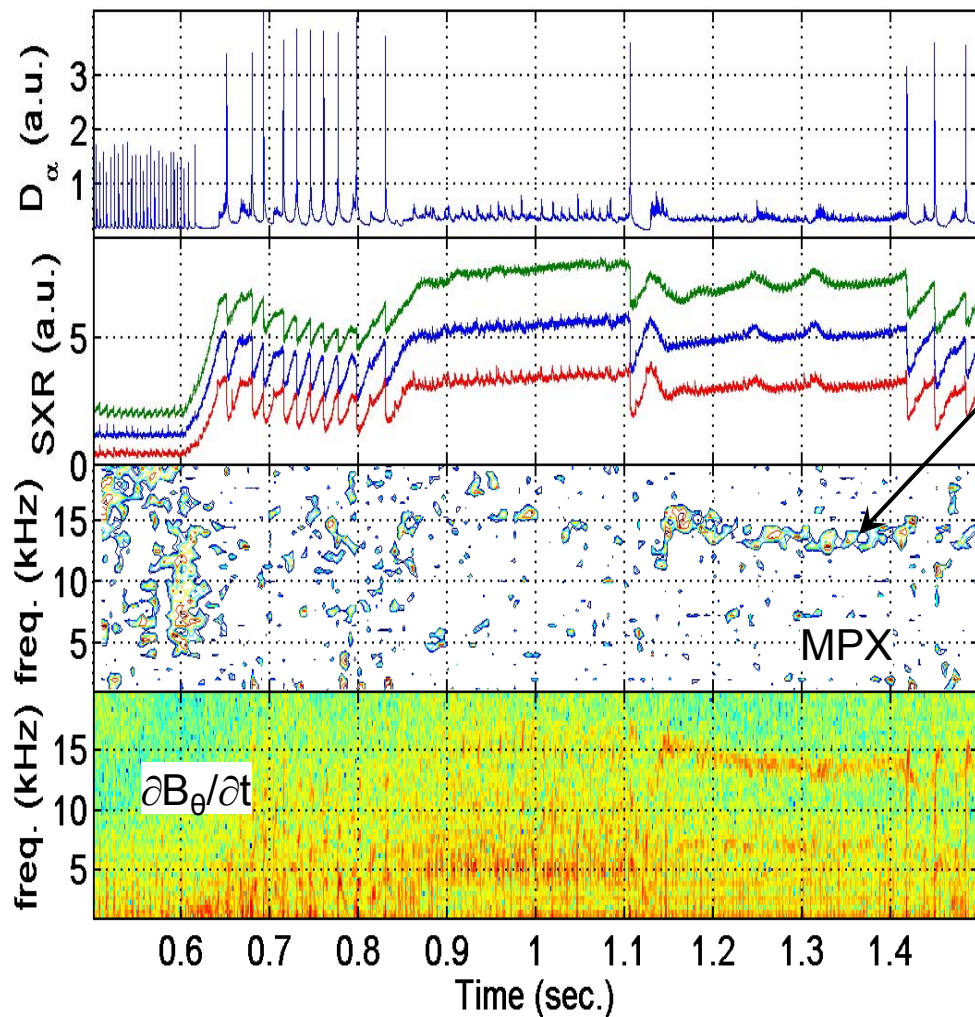
QSEFHM: CONFINEMENT & MHD



- $\tau_E \approx 27\text{msec}$
- $H_{ipb98(y,2)} \approx 1.4$
- $n_{e,o} / \langle n_e \rangle \approx 1.5$
- Confinement degraded by the appearance of core MHD

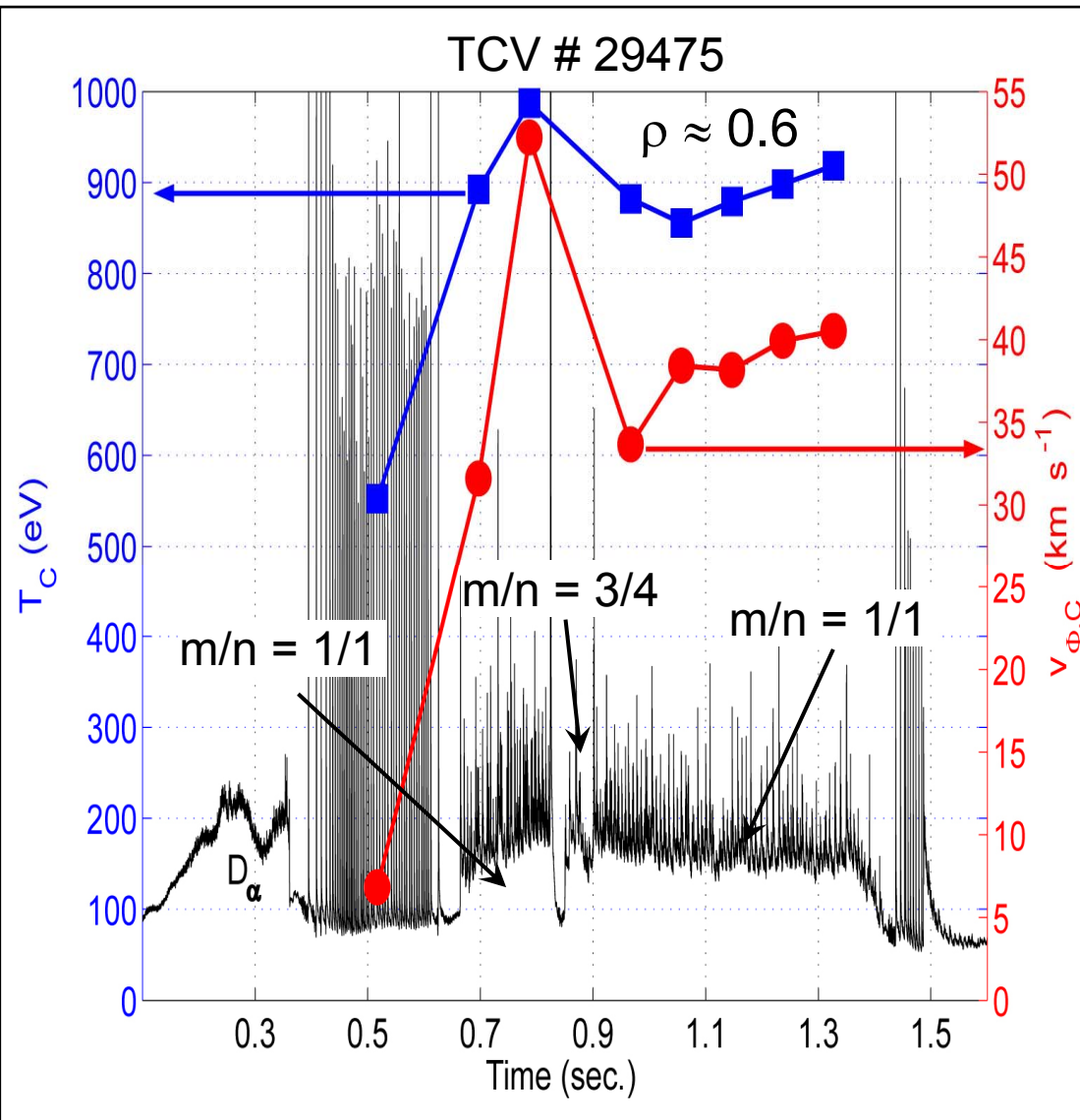
QSEFHM: CONFINEMENT & MHD

TCV #29892



- $m/n = 1/1$ modes dominate during the 'high performance' phase (SAWTEETH)
- $m/n = 4/3$ modes (NTMs ?) also appear and these degrade the confinement
- No mode similar to the EHO has been detected to date
- Density control not understood
- D_α light fluctuations strongly correlated with core MHD

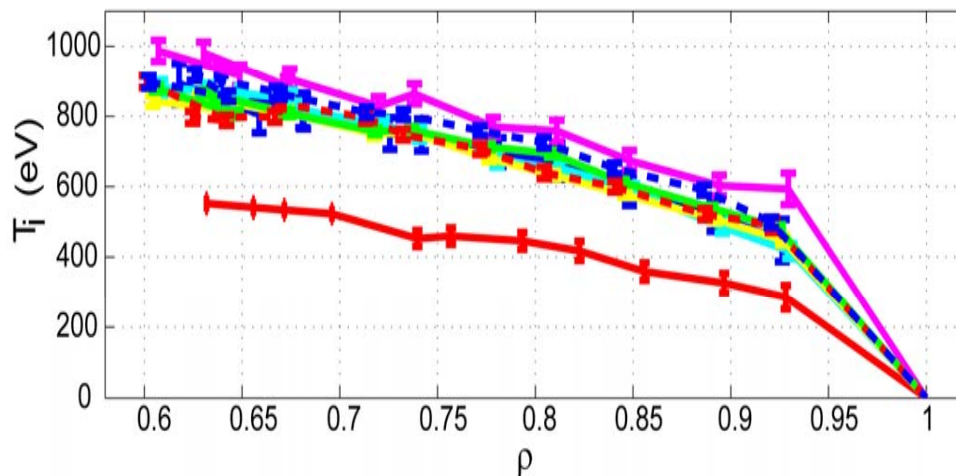
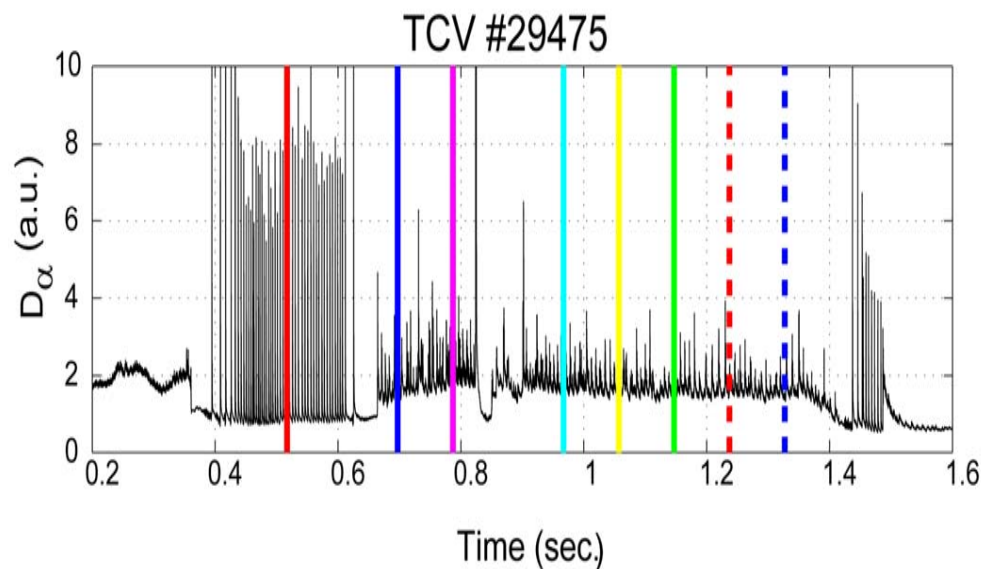
QSEFHM : ION BEHAVIOUR



- Shot similar to 29892
- CXRS measurements in unique conditions
- Significant collisional ion heating; T_i doubles
- $v_\phi \uparrow$ at onset of QSEFHM
- $v_\phi \propto T_i^{**}$ during the QSEFHM
- It is *not clear* that ion heating & toroidal rotation are features particular to QSEFHM
- MHD moderates T_i (confinement) and rotation

** Scarabosio et al : $v_\phi \propto -T_i / I_p$ in L-mode : PPCF **48** (2006) 663-683

QSEFHM : ION BEHAVIOUR



- X3 goal → access high n_e
→ heat ions
- Achieved in these discharges
- $\rho \approx 0.6$ we have $T_i \approx 1\text{keV}$
- $T_{i,\rho=0}$ higher ($\approx 1.5\text{keV}$?)
- $\tau_{e,i} \approx 90\text{msec}$: ions heated on this time scale
- $\approx 18\%$ coupled ECRH power to ions
- no sign of fast ions (NPA)
- first time on TCV
- door open to H-mode studies :
massive electron heating
indirect ion heating



QSEFHM : Unique ?

- It is our contention that the TCV QSEFHM is unique
- New mode does not resemble any other ELM-free high confinement regime seen elsewhere :

QH-mode (DIII-D, JT-60U, JET, ASDEX) requires counter current NBI, cryo-pumping of divertor

EDA H-mode (ALCATOR) : $q_{95} > 3.7$, broadband, coherent fluctuations ($f_{\text{fluc}} \approx 100\text{kHz}$)

RI-Mode – high Z impurities, $n_e/n_G > 0.8$ and $v_{\text{eff}} > 1$

Type II ELMS – $q_{95} > 4.0$ required & $n_e/n_G > 0.8$ and $v_{\text{eff}} > 1$



QSEFHM : SUMMARY

- Require $P_{x3,coupled} > 1.2\text{MW}$ to access QSEFHM
- significant : ELM-free High Confinement Mode occurring at fusion relevant plasma parameters ($\beta_N \approx 2$, $v_{eff} \approx 0.4$ and $q_{95} \approx 2.5$)
- unique : differs in many respects to other very similar regimes found elsewhere
opportunity to study rotation, in high power, high confinement regime with no external momentum input
- transition to quasi-stationary ELM free mode not yet understood
- energy confinement better than IPB98(y,2)
modelling effort underway (Asp, Horton et al Sherwood meeting 2007)@
ASTRA & GFL23 used to model confinement
BOTH underestimate the energy confinement time
GLF23 fails to predict the increase in τ_E at transition from ELMy to QSEFHM (29892)
- Stationary density has yet to be explained: no 'edge harmonic oscillation' observed to date; core MHD ? Fluctuation diagnostics (correlation ECE & phase contrast imaging) to be installed



SUMMARY & CONCLUSIONS

- high harmonic (X3) ECRH has proven an effective heating method on TCV
- cryogenically cooled sapphire gyrotron windows → problematic
one has already been replaced by a CVD diamond window
increase gyrotron power output
- H-mode heating experiments have been very successful
collisional ion heating observed in an ECRH heated H-mode plasma
≈80% first pass absorption obtained
- new quasi-stationary ELM-free H-mode regime obtained
ion temperature doubles ; collisional ion heating
high energy confinement
massive toroidal rotation increase observed at the onset of X3 heating (no external momentum input)